Calorimetry of gamma-ray bursts: echos in gravitational waves

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ABSTRACT

Black holes surrounded by a disk or torus may drive the enigmatic cosmological gamma-ray bursts (GRBs). Equivalence in poloidal topology to pulsar magnetospheres shows a high incidence of the black hole-luminosity L_H into the surrounding magnetized matter. We argue that this emission is re-radiated into gravitational waves at $L_{GW} \simeq L_H/3$ in frequencies of order 1kHz, winds and, potentially, MeV neutrinos. The total energy budget and input to the GRB from baryon poor jets are expected to be standard in this scenario, consistent with recent analysis of afterglow data. Collimation of these outflows by baryon rich disk or torus winds may account for the observed spread in opening angles up to about 35°. This model may be tested by future LIGO/VIRGO observations.

Subject headings: black hole physics — gamma-rays: bursts and theory – gravitational waves

1. Introduction

It is now widely believed that progenitors of GRBs are massive stars or black hole-neutron star binaries. These systems have ample and well-defined energy in angular momentum to produce the relativistic outflows which drive GRBs. Support for hypernovae in massive stars (Woosley 1993; Paczyński 1997, 1998; Brown et al. 2000) derives from an association with star-forming regions (Paczyński 1998; Bloom et al. 2000), the GRB 980425/SN 1998bw event (although this source exhibits markedly different properties than a typical burst) and a potential GRB/Soft X-ray transient connection (Brown et al. 2000, 2001), e.g., as in GRO J1655-40 (Israelian et al. 1999) and V4641 Sgr (Orosz et al. 2001). Chemical abundances in the latter have been attributed to the intercept of hypernova-debris by the secondary during the GRB-event. A likely outcome of the collapse of a massive star is a black hole surrounded by a disk or torus. The coalescence of black hole-neutron star binaries may likewise produce black hole-torus systems when the black hole spins rapidly (Paczyński 1991). This remains of interest in view of their occurence rate (Phinney

1991; Narayan et al. 1991; Brown et al. 1999) which, although marginally, is consistent with GRB statistics set by estimates of the beaming factors (see below).

In this *Letter*, we classify the major channels of radiation from black hole-torus systems and provide estimates for their net fluences (see van Putten (2001) for a review). Outflows powered directly by the black hole enables baryon poor input to the GRBs. Radiation from the torus establishes channels for "unseen" emissions: gravitational radiation, Poynting flux-dominated and baryonic collimating winds and, possibly, neutrino emissions. In the GRB/SXT-association of Brown et al. (2000, 2001), these emissions are augmented by hypernova disk-winds which provide a chemical deposition of metals onto the companion star. We shall find that a dominant fraction of the energy will be liberated in gravitational waves. As predictions for future calorimetry in multi-window observations, estimates of the fluences in these "unseen" emissions may provide the most stringent observational test of the black hole-torus system. As an observational test for the black hole-torus association to gamma-ray bursts, we may further consider recovering the the present bi-modal distribution in durations in the BATSE catalogue in these unseen radiation channels.

Recent analysis of afterglow data in GRBs with measured redshifts appears to indicate a standard energy release of prompt gamma rays in long bursts, and a rather wide range of observed beaming factors (Frail et al. 2001). Below, we argue that standard energy release and a range of collimation factors is a natural consequence of black hole-torus systems in a suspended accretion state, which we associate with long bursts van Putten & Ostriker (2001).

In §2, the basic features of black hole plus disk or torus systems is summarized. §3 discusses the clustering-and-spread in leptonic outflows from black hole-torus systems. §4 presents an outlook for unseen emissions in gravitational waves.

2. Non-thermal emissions from black hole-torus systems

The black hole-torus system represents hypernovae, or the expected outcome of black hole-neutron star coalescence. The torus forms as remnant matter of a fallback envelope of a massive star or as the debris of a neutron star. A net magnetic flux carried by the torus supports a similarly shaped magnetosphere. Surrounded by a magnetic field with net poloidal magnetic flux, the central black hole assumes an equilibrium magnetic moment (van Putten 2001)

$$\mu_H^e \sim aBJ_H, \tag{1}$$

where $a = J_H/M$ denotes the specific angular momentum of a black hole with angular momentum J_H and mass M, and B the field-strength of the torus magnetosphere. The magnetic moment given by eq. (1) is no "fourth hair" of the black hole (Carter 1968): it is generated by an equilibrium charge $q^e \sim BJ_H$ of the black hole (Wald 1974; Dokuchaev 1987; Lee et al. 2001). This magnetic moment serves to regulate an essentially uniform and maximal horizon flux, preserved at arbitrary rotation rates. This permits the horizon to couple to the inner face of the torus and to support of

an open flux-tube to infinity (van Putten 2001). The net horizon luminosity L_H is, correspondingly, the sum of a luminosity L_T into the torus and a luminosity L_p to infinity.

Equivalence in poloidal topology to pulsar magnetospheres indicates a high incidence of the black hole-luminosity – by way of Maxwell stresses – into the surrounding magnetized matter (adapted from Goldreich and Julian (1969); Thorne et al. (1986); van Putten (1999); Brown et al. (2001))

$$L_T = \omega_T(\omega_H - \omega_T)f_T^2 A_H^2, \tag{2}$$

where f_T denotes the fraction of poloidal horizon flux $2\pi A_H$ which connects to the torus, and ω_T, ω_H denote the angular velocities of the torus and the black hole, respectively. A suspended accretion state arises when ω_H/ω_T is sufficiently large van Putten & Ostriker (2001).

Leptonic outflows are produced by rotating black holes in an open flux-tube along their axis of rotation, in response to differential frame-dragging (van Putten 2000a; Heyl 2001; van Putten 2001). This open flux-tube is endowed with conjugate radiative-radiative boundary conditions, at the horizon and finity. Global closure of the current – asymptotically null in the force-free sections on the horizon and infinity – over an outer flux-tube supported by the torus gives rise to a net luminosity in $e^{\pm}\gamma$ given by (van Putten 2001)

$$L_p = \frac{1}{2}\omega_T(\omega_H - 2\omega_T)f_o^2 A_H^2, \tag{3}$$

where f_o denotes the fraction of poloidal horizon flux which supports the open flux-tube. This in situ creation of leptonic outflows takes place whenever the black hole rotates faster than *twice* the angular velocity of a torus in prorate rotation.

The energetic coupling (2) permits a high luminosity L_{GW} in low-frequency gravitational-wave emissions from the torus, by generic non-axisymmetric deformations. A time-averaged luminosity can be estimated in the suspended accretion state van Putten & Ostriker (2001). When most of the magnetic field on the horizon is anchored to the surrounding matter, i.e. $f_T \simeq 1$, we have $L_H \simeq L_T$ and hence (van Putten 2001)

$$L_{GW} \simeq \omega_T^2 A_T^2 \simeq L_H/3, \tag{4}$$

where $2\pi A_T$ denotes the net poloidal flux in the torus. Here, $\omega_T/\omega_H \simeq f_H^2/3$ in terms of the fraction f_H of the flux supported by the torus which connects to the horizon of the black hole (van Putten 2000a).

An appreciable fraction of (2) may dissipate in the disk, probably giving rise to emission of neutrinos if maintained at high enough temperatures, and perhaps other forms of radiation. The torus may loose baryon rich material at a substantial rate. This may provide a baryonic collimating wind launched along the open flux tubes (see below), and a chemical deposition of metals onto the companion star.

To summarize, the work performed by the black hole as it sheds off its angular momentum in the course of the evolution to a lower energy state (cf. the Rayleigh criterion), is liberated through two important channels (van Putten 2001):

I Baryon poor outflows along open flux-tubes supported by the spin-energy of the black hole (van Putten 2000a; Heyl 2001; van Putten 2001) that, we conjecture, provide the free energy source that powers GRBs. This work is proportional to $f_o^2 = (\Omega_H/4\pi)^2 <<$ 1, whereby the remaining fraction $f_T \simeq 1$. The important GRB emissions form a small fraction of the total luminosity L_H of the black hole.

II Gravitational wave-emissions from non-axisymmetric deformations in the torus, powered by about one-third of the black hole luminosity. These frequencies are correlated with the Keplerian angular velocity of the torus and, hence, of the order of 1kHz – low frequencies relative to the quasi-normal mode oscillations of the black hole.

In the hypernova model of Brown et al. (2000, 2001), a third channel consists of disk winds providing chemical depositions of metals onto the companion star. The energy $\sim 10^{52}$ erg in these winds (Maeda et al. 2001) may derive from L_T by a safe margin (see below). Unknown is the role of analogous baryonic winds from black hole-torus systems formed in mergers of black hole-neutron star binaries.

3. The true energy budget and clustering-and-spread in outflows

The fraction of the hole rotational energy liberated as leptonic outflows is approximately $(\Omega_H/4\pi)^2 << 1$, where Ω_H is the solid angle on the horizon occupied by an open flux-tube (van Putten 2001). The remaining spin down energy is deposited in the torus as described in (II) above. By the first-law of black hole-thermodynamics, the efficiency of delivering spin-energy into the surrounding torus is given by the ratio of angular velocities $\omega_T/\omega_H = 2/((R/M_H)^{3/2} + 1)$ of the torus and black hole, respectively, for a maximally spinning black hole. Here, R denotes the radius of the torus and M_H the mass of the black hole, assuming the torus to be in approximately Keplerian motion. For a conservative value $\omega_T/\omega_H \sim 0.1$, the available black hole energy of a maximaly rotating black hole is

$$E_H \simeq 4 \times 10^{53}(M_H/7M_\odot) \text{ ergs.} \tag{5}$$

Here, the fiducial scale of $7M_\odot$ is motivated by the range of about $4 - 14M_\odot$ in dynamically determined masses of black hole candidates in X-ray novae (see van Putten (2001) for a recent update).

The suspended accretion state is expected to result in a relatively thick torus, as it will be hot and in a state of super-/sub-Keplerian motion at the inner/outer face due to the powerful

competing torques acting on it. This promotes a radially slender and a poloidally extended shape. It should be mentioned that the torus mass and magnetic-to-kinetic energy ratio are the two main uncertain parameters, also in regards to the time-scale of the suspended accretion state (van Putten & Ostriker 2001).

A relatively thick torus produces a funnel surrounding the black hole. The horizon solid angle Ω_H of the open flux-tube on the horizon will depend on the poloidal structure of the torus magnetosphere surrounding the black hole – as supported by the inner face of the torus in its immediate vicinity. Tori with inner faces larger than the black hole size are expected to give rise to a similar poloidal topology of the torus magnetosphere surrounding the black hole, and hence similar solid angles Ω_H. This leads to the expectation that both, the total black hole energy, E_H, and the fraction emerges along the open flux tubes, E_j, should be standard. Adopting the estimate by (Frail et al. 2001) for the true energy of prompt emission (in bi-polar outflows): $\bar{E}_\gamma \simeq 5 \times 10^{50}$ ergs, we obtain

$$\Omega_H/4\pi = (E_j/E_H)^{1/2} \simeq 0.1(M_H/7M_\odot)^{-1/2}(\epsilon/0.1)^{-1/2}, \tag{6}$$

where ϵ denotes the conversion efficiency of bulk energy of the leptonic outflow into gamma rays. While existing models vary in their estimates of ϵ, an approximate mean value of about 0.15 appears to be reasonable for GRB emission from internal shocks (Kobayashi et al. 1997; Daigne & Mochkovitch 1998; Guetta et al. 2000; Panaitescu & Kumar 2000). Radiative viscosity mediated through the agency of some background radiation field (a component that may be particularly relevant for the class of models considered here) may enhance the efficiency of internal shocks considerably (Levinson 1998). Alternatively, high efficiency (as well as a preferable νF_ν peak of prompt emission) can be naturally achieved in compact fireball models, whereby prompt GRB gamma rays near the peak of the spectral energy distribution are produced on compact scales, prior to the acceleration of the fireball to its terminal Lorentz factor (Eichler & Levinson 2000). Thus, a value of $\Omega_H/4\pi \sim 0.1$, corresponding to an opening angle

$$\theta_H \simeq 35^\circ, \tag{7}$$

seems reasonable. Given the observed mean beaming factor, $\bar{f}_b \sim 2 \times 10^{-3}$, this generally implies that the baryon poor outflow should be further collimated into a solid angle $\Omega_j \sim \Omega_H/30$. Further collimation may proceed through interactions with the baryon rich wind surrounding it (Levinson & Eichler 2000). If the disk or torus is initially hot (at MeV temperature) and dense, as anticipated if it forms as a result of collapse of a massive star or coalescence of compact objects, then it will first cool down over a timescale of several seconds via neutrino emission. During this process a fraction η (a few percent) of a solar mass will be blown off, carrying a total energy of order $\eta M_\odot c^2$ (Levinson & Eichler 1993). Additional mass loss may arise from the interaction of the black hole and the torus, as mentioned above.

The degree of collimation depends on the parameters of the baryonic wind, which in turn might be sensitive to the conditions in the disk (as well as its structure) and is, therefore, expected

to exhibit large variations. This can explain the diversity of beaming factors exhibited by the sample studied in (Frail et al. 2001). Preliminary analysis (Levinson & Eichler 2000) shows that the opening angle of the fireball thereby collimated is proportional to the ratio of luminosities of the baryon poor and baryon rich outflows. For a GRB having a beaming factor of order the mean found by (Frail et al. 2001); e.g., GRB 990123, we find that the energy E_{cw} on the confining wind is roughly

$$E_{cw} \simeq (2f_b)^{-1/2} E_j \epsilon^{-1} \simeq 5 \times 10^{52} \text{ ergs}, \tag{8}$$

below the total energy deposition in the torus by a safe margin (see eq. [5]). Further work is needed to quantify the relation between the collimation factor and the luminosity of the baryonic wind for a broader range of physical conditions, and for different assumptions on the boundary conditions.

4. Gravitational-wave bursts from black hole-spin in long GRBs

There are at least five aspects to a black hole-torus system which suggest considering their potential as LIGO/VIRGO sources of gravitational radiation, produced by emissions from the torus. By equivalence in poloidal topology to pulsar magnetospheres, the torus is strongly coupled to the spin-energy of the black hole (van Putten 1999; van Putten & Ostriker 2001); non-axisymmetric deformations in the torus will produce gravitational and radio emissions (modulations) at low frequencies (relative to those of the quasi-normal modes of the horizon), e.g., at twice the Keplerian frequency if produced by lumpiness; compact magnetized objects which reach their Schwarzschild radius with gravitationally weak magnetic fields, radiate predominantly in gravitational rather than electromagnetic waves (cf. young pulsars, e.g., Shapiro and Teukolsky (1983)); non-axisymmetric deformations in the torus are expected by instabilities, such as from self-gavity and consistent with the requirement for intermittency at the source (Piran 1998); the true rate of GRBs should be frequent, as inferred from their large beaming factor (Frail et al. 2001).

The gravitational wave-luminosity can be calculated in a suspended accretion state (van Putten 2001). The frequencies will be, to leading order, related to the Keplerian angular velocity of the torus. On the secular time-scale of spin-down of the black hole, these frequencies will trace a horizontal branch in the $\dot{f}(f)$−diagram (van Putten and Sarkar 2000). In particular, lumpiness in the torus produce a gravitational-wave frequency at twice the Keplerian frequency (van Putten 2001):

$$f_{gw}(t) \sim 1 - 2\text{kHz}/(1+z), \quad \mathrm{d}f_{gw}(t)/\mathrm{d}t = \text{const.} \tag{9}$$

Here, canonical values are used for a black hole-torus system at redshift z. Other frequencies may arise as described in studies of QPOs (cf. Stella (2000)). If the torus is unstable against breaking up in clumps, or if the torus shows violent expansions in its mean radius, the gravitational waves will be episodical, and will correlate with sub-bursts in long GRBs. It should be mentioned that the horizontal branch may be above or below the f−axis, corresponding to a positive or negative

linear chirp in the frequency dynamics. This uncertainty results from the uncertainty in the details of the radial dependence of the fraction of interconnecting field-lines between the black hole and the inner face of the torus as a function of major radius of the torus.

The torus is expected to be luminous also in winds and, when sufficiently hot, neutrino emissions. The energy liberated in gravitational radiation, winds, and neutrinos may be roughly equal (van Putten 2001). By eq. (4), the black hole luminosity (eq. [5]) into the torus serves as an estimate for the energy released in gravitational waves:

$$E_{gw} \simeq 10^{53}(M_H/7M_\odot) \text{ ergs.} \tag{10}$$

Since gravitational-wave emission is essentially unbeamed, the beaming factor ~ 500 found by Frail et al. (2001) suggests that long GRBs, observed at redshifts of order unity, take place as gravitational wave-bursts at a rate of few$\times 10^5$/year, or a few times per year within a distance of 100Mpc. With their gravitational emissions (eq. [10]) in the frequency range given by eq. (9) this suggests that long GRBs are potentially powerful LIGO/VIRGO burst-sources of gravitational radiation (van Putten 2001).

The above suggests at least three aspects to future LIGO/VIRGO observations. LIGO/VIRGO may quantitatively probe the inner most structure of black hole-torus systems by tracking the secularly evolving frequencies. A link to GRBs may be established by comparing duration statistics from these LIGO/VIRGO detections with the BATSE catalogue (after redshift corrections). A link to a binary progenitor system may be made by searching for a progenitor chirp to the emissions from the torus. If present, it would be of interest to consider extracting the individual binary masses by combining the chirp mass from precursor emissions with the black hole mass determined from the (secularly evolving) frequencies from the torus.

5. Summary and Conclusions

A black hole surrounded by a disk or torus is a likely outcome of the collapse of a massive star or coalescence of compact objects and may power the enigmatic GRBs. The rotational energy of the black hole should be released both along the axis of rotation and into the equatorial plane owing to its interaction with the surrounding disk or torus. Baryon poor outflows are expected to be produced along the axis of rotation, while Maxwell stresses dominate the energetics onto the surrounding magnetized matter. A torus will re-radiate the latter in gravitational waves, winds and, possibly, neutrinos.

Sufficiently thick tori should yield a similar poloidal structure of the magnetosphere in the neighborhood of the black hole and, hence, roughly similar opening angles of the outflow on the horizon, leading to the extraction a standard fraction of the spin-energy in the form of outflows that power GRBs. This can quite naturally account for the inferred clustering of GRB energies. The initial cooling of the torus, and subsequent dissipation of some fraction of the unseen hole energy,

will drive considerable mass loss of baryons from the torus. Collisions of the baryon poor outflows and the baryon rich winds can provide a collimation mechanism. As the degree of collimation depends on the wind parameters, and might be sensitive to the specific conditions in the torus, it should lead to a range of opening angles for the collimated leptonic outflows, which may explain the observed spread of beaming factors. The same power input to the disk or torus is expected to expell baryonic winds in the equatorial plane, which may account for the chemical depositions in metals onto the companion star (Brown et al. 2000, 2001).

A standard total hole energy and the fraction powering the associated GRB determines the solid angle Ω_H occupied by the open flux tubes near the horizon. This relates to gravitational waves as a potentially new observable, and to the true energy of the prompt GRB emission. If Ω_H is indeed similar in all sources, it will appear as a break in the distribution of opening angles (cf. (7)) that may be observable in a large enough sample, and can serve as an important test for this model.

A major fraction of the rotational energy of the black hole is predicted to be liberated in gravitational waves which overlap with the bandwidth of advanced LIGO/VIRGO. Determining this power output promises true calorimetry of black hole-torus systems.

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